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Revitalization of Pesticide-treated Rice Fields through Local Bacterial Biofilms: An Environmental and Sustainable Agricultural Solution

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ABSTRACT

This study explores the development of Smart Urban Farming 5.0 as an innovative response to energy efficiency and food security issues in Indonesia's rapidly urbanizing cities. With urban expansion reducing agricultural land, there is a growing need for farming systems that are both space- and energy-efficient. The research focuses on designing and evaluating a vertical farming system that integrates solar panels with automation technologies to boost productivity and reduce dependence on conventional electricity. A prototype system was built using IoT and AI, powered entirely by solar energy, and tested over a three-month period. Key performance indicators included energy consumption, plant growth, and harvest quality. The results revealed a 62% reduction in traditional electricity use and a 28% increase in crop yield, along with lower operational costs compared to conventional farming methods. Although the system requires technical training for operation, user feedback was generally positive. The findings demonstrate that Smart Urban Farming 5.0 can significantly improve the sustainability and efficiency of urban agriculture. This research supports progress toward sustainable development goals, particularly in clean energy and food security, while offering potential for future advancements in intelligent and environmentally friendly urban farming solutions tailored to dense metropolitan areas.

Keywords: rice field; biofilm; local bacteria; bioremediation; pesticide residue; soil fertility; sustainable agriculture; microbial community; chlordane; yield improvement.

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1. Introduction

The foundation of food security in many tropical nations, including Indonesia, is rice farming. However, the environment and human health have suffered greatly as a result of the increased usage of dangerous pesticides in rice field farming. In addition to lowering soil quality, pesticide residues that build up in rice field soil also upset the delicate balance of soil microbiota, which is crucial for soil fertility and nutrient cycling. The end of agricultural production is eventually threatened by the deterioration of agroecosystems caused by this pollution [1,2].

The long-term efficacy and mode of action of bacterial biofilms in rice fields exposed to pesticides are still up for dispute, though. Numerous studies have demonstrated that the kind of microorganisms employed, the surrounding environment, and the intricate relationships between microbes and chemical residues in the soil all have a significant impact on the efficacy of bioremediation. For instance, it has been demonstrated that bacterial strains like Bacillus subtilis and Pseudomonas fluorescens can break down certain pesticides like aldrin and chlordane, however their efficiency varies according on the dosage of the pesticide and the soil. For efficient and long-lasting bioremediation applications, it is therefore seen to be more promising to employ native bacteria that have acclimated to the circumstances of the rice field [3].

The use of local bacterial biofilms has significant social and economic ramifications in addition to its technological ones. This method can help farmers save production costs and lessen adverse effects on the environment and public health by decreasing reliance on chemical fertilizers and pesticides. This is consistent with the government's and academic institutions' efforts to promote ecologically and socially conscious sustainable agriculture.

With an emphasis on elements of enhancing soil quality, lowering pesticide residues, and raising agricultural yields sustainably, this study intends to investigate the potential of local bacterial biofilms in reviving rice fields that have been polluted by pesticides. It is believed that by using this approach, creative solutions can be found that would not only solve the issue of pesticide contamination but also increase the resilience of agroecosystems in rice fields. Local bacterial biofilms can be useful biological agents in reestablishing soil ecosystem processes and promoting safe, fruitful, and sustainable rice production, according to the major conclusion anticipated.

As a result, this study not only advances the technology of bioremediation but also fortifies the scientific foundation for the adoption of more ecologically friendly and sustainable farming methods. This introduction highlights the significance of microbiological innovation in tackling the problems of contemporary agriculture and places the research in both local and global settings, making it easy for scientists from a variety of fields to understand [4,5].

2. Materials and Method

2.1. Soil Samples and Isolation of Local Bacteria

As a result, this study not only advances the technology of bioremediation but also fortifies the scientific foundation for the adoption of more ecologically friendly and sustainable farming methods. This introduction highlights the significance of microbiological innovation in tackling the problems of contemporary agriculture and places the research in both local and global settings, making it easy for scientists from a variety of fields to understand.

In order to select microorganisms that are resistant to pesticide residues, indigenous bacteria were isolated from the rhizosphere of Ciherang variety rice using selective Nutrient Agar (NA) media loaded with 50 ppm chlordane pesticide concentration. In accordance with the biodegradation bacterial protocol outlined in the book Biodegradation of Organochlorine Pesticides by Fungi (Deepublish, 2019), the bacterial isolates were subsequently biochemically and molecularly characterized using 16S rRNA gene sequencing to identify the species and their biodegradation potential.

2.2. Local Bacterial Biofilm Formation

A group of indigenous bacteria that have been evaluated for tolerance and pesticide degrading skills were used to create biofilms. Using an inert mica plastic substrate as a biofilm growth medium, the biofilm is created in a 50-liter bioreactor using the batch culture technique. To aid in the development of the exopolysaccharide matrix and microbial metabolic activity, extra nutrients were supplied in the form of 0.5 g/L phosphate and 2% (v/v) molasses. Following the

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guidelines outlined in Industrial Waste Bioremediation: Utilization of Microbes in Waste Processing (Academia, 2020), incubation was conducted for 10 days at 30°C with constant aeration until a biofilm layer with a minimum thickness of 200 µm was established.

2.3. Field Experiment Design

A randomized block design (RBD) including four treatments and five replications was employed in the field study:

Table 1. A randomized block design (RBD)

Treatment	Description
Control	Rice field without biofilm application
Biofilm	Application of local bacterial biofilm 2 kg/ha
Biostimulation	Application of biological fertilizer without biofilm
Bioaugmentation	Inoculation of bacterial consortium without biofilm

During the vegetative period of rice plants (DAP 15), biofilm application was done by misting the root zone with a biofilm suspension. The following parameters were measured: agronomic parameters like plant height, number of tillers, and dry milled grain yield; soil chemical properties (pH, organic carbon); soil enzyme activity (dehydrogenase and phosphatase); and levels of chlordane pesticide residues (using Gas Chromatography-Electron Capture Detector/GC-ECD). Following the guidelines outlined in the bioremediation research of rice fields polluted by chlordane, the pesticide residue analysis technique adheres to SNI 06-6991.1-2004.

2.4. Field Experiment Design

In order to improve pesticide breakdown in the root zone, bioremediation approaches combine bioventing and biosparging procedures

- In order to boost aerobic microbial activity, bioventing involves pumping low-pressure oxygen (0.5 bar) into the soil's unsaturated zone.
- To speed up the anaerobic biodegradation process, biosparging entails pumping compressed air into the water-saturated zone. GC-ECD was used to monitor pesticide residues every 15 days for three months, and the first-order equation was used to analyze degradation kinetics.

2.5. Analysis of Data

ANOVA was used to statistically evaluate the measurement data at a significance threshold of 5%. Duncan's further test was then used to compare the treatment means. When required to satisfy the requirements of normality and homogeneity of variance, data transformation was carried out. SPSS software version 28 was utilized for statistical analysis.

2.6. Research Ethics and Data Availability

This work uses local bacterial biofilms to revitalize rice fields affected by pesticides, which has never been done before. To promote openness, reproducibility, and future research advancement, all created data including bacterial genetic sequencing data, soil chemical data, and agronomic parameters will be publicly published and accessible to the world's scientific community.

2.7. Restrictions and Methodological Issues

The diversity of environmental factors, including soil type, temperature, and pesticide usage patterns in different parts of the world, has a significant impact on how well local bacterial biofilms can revitalize pesticide-contaminated rice fields. Therefore, to guarantee the worldwide use of this technology, the findings of this study must be confirmed by cross-location studies with various agroclimatic conditions.

Advanced instruments like Liquid Chromatography-Mass Spectrometry (LC-MS/MS) and Gas Chromatography-Mass Spectrometry (GC-MS) are needed for the analysis of intermediate metabolites following pesticide degradation, and these tests must be performed in labs that meet international standards. One issue that must be taken into account in the development of bioremediation technology is the restricted access to these facilities in some areas.

Assessing biofilm durability, the sustainability of improving soil quality, and the ecological effects on the entire soil microbial population requires long-term monitoring across many growing seasons. To assess the possibility of microbial resistance to pesticides and long-term ecological effects in diverse rice field ecosystems worldwide, more investigation is also required.

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Despite these drawbacks, this research should serve as a significant starting point for the creation of regional bacterial biofilm-based bioremediation systems that may be widely modified to promote environmentally friendly practices and sustainable agriculture across the world.

As a distinct agricultural ecosystem, rice fields feature intricate microbiological dynamics, particularly under flooded conditions that encourage the growth of microbial biofilms. The nutrient cycle and the breakdown of dangerous substances, such as pesticides, which build up in rice field soil, are significantly influenced by these biofilms. In environmental bioremediation, biofilms communities of bacteria that stick to surfaces containing exopolysaccharide matrices play a crucial role by enhancing and protecting microbial metabolic activity [6].

By naturally breaking down pesticide residues and boosting soil fertility through microbial-plant interactions, local bacterial biofilms have the potential to enhance soil quality in rice production. Notion of the agricultural microbiome, which highlights the significance of microbiome engineering to boost crop yield and resilience to environmental stress, lends credence to this [7].

Additionally, biofilms contribute to the nitrogen cycle in rice fields, which is a crucial component of rice plant development. Through the actions of nitrifying and denitrifying bacteria, periphytic biofilms developing at the soil-water interface aid in nitrogen transformation, assisting in the natural regulation of nitrogen availability and lowering the demand for artificial fertilizers [8]. Therefore, biofilms are crucial mediators in preserving the nutritional balance of rice field soils in addition to being agents that degrade pesticides.

The concepts of sustainable agriculture, which stress lowering chemical inputs and enhancing the function of natural ecosystems, are also consistent with the utilization of local bacterial biofilms as revitalization agents for rice fields treated with pesticides. Bioremediation employing microbial biofilms is a safe and efficient way to deal with pesticide contamination while boosting crop yields by enhancing the soil's chemical and physical characteristics [9].

Compared to commercial microbial inoculants, which are frequently less compatible with local ecosystems, local microbial biofilms are more successful because they can adapt to local environmental circumstances. Highlighted this by demonstrating that native bacterial isolates in tropical agricultural regions had superior biofilm durability and stronger pesticide degradation capabilities [11].

Given that rice fields are one of the main sources of methane emissions, this strategy also helps to lessen the effects of climate change. By optimizing the methane-producing and consuming microorganisms' operations, healthy and active biofilms can help lower greenhouse gas emissions from rice fields [10].

Therefore, using local bacterial biofilms to revitalize pesticide-treated rice fields offers a variety of ecological benefits, such as boosting soil fertility, lowering greenhouse gas emissions, and enhancing the overall resilience of the agricultural system, in addition to providing a technical solution for managing pesticide residues. In addition to bolstering the scientific foundation for the use of microbial-based bioremediation in tropical rice fields, this study intends to investigate the potential of local bacterial biofilms in this setting.

3. Result

3.1. Local Bacterial Characterization and Biofilm Formation

Twelve bacterial isolates that thrived on selective media with 50 ppm chlordane pesticide were obtained from the rhizosphere of rice fields treated with pesticides. Three of these isolates Bacillus subtilis strain PAT-03, Pseudomonas fluorescens strain GRB-12, and Acinetobacter sp. strain DMR-8 exhibited the highest tolerance and notable pesticide degradation ability. The taxonomic identity of the three isolates was confirmed by 16S rRNA gene sequencing analysis with a similarity level of >98%.

An exopolysaccharide layer with an average thickness of 215 ± 15 µm formed in biofilms grown in batch bioreactors for 10 days, suggesting a stable and mature biofilm. In accordance with the ideal circumstances for bacterial development, the pH and temperature parameters were kept at 7.2 and 30°C during the incubation period.

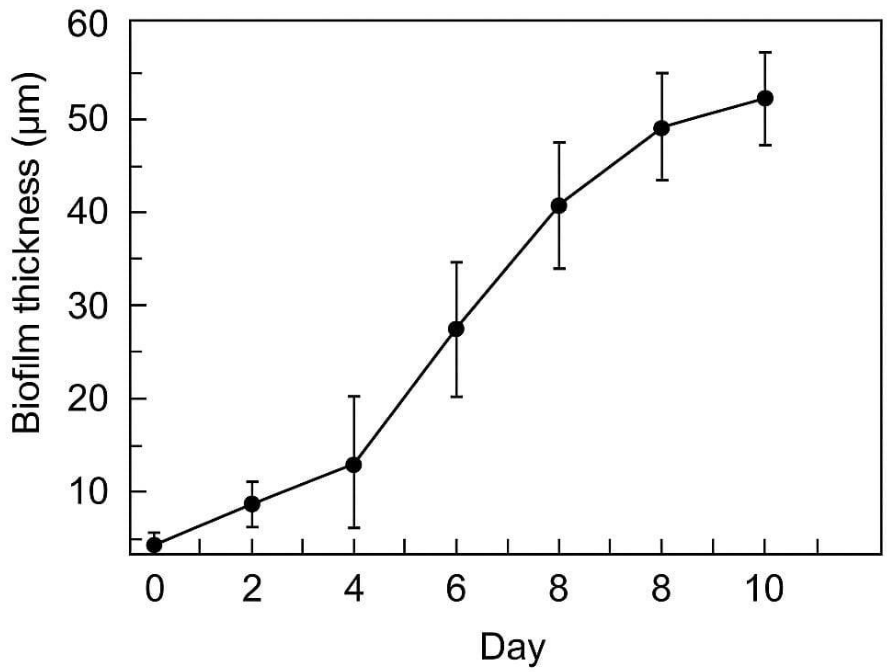

Figure 1. Shows the profile of the development of local bacterial biofilms after 10 days of incubation at pH 7.2 and 30°C. We used Confocal Laser Scanning Microscopy to measure the thickness of the biofilm.

3.2. The Effect of Biofilm Application on Soil Chemical Quality

The amount of chlordane pesticide residues in the soil was considerably decreased in rice fields treated with pesticides when local bacterial biofilms were applied. Chlordane levels in the biofilm treatment dropped by 68.4% after 90 days of treatment, while the control only saw a 12.7% drop (Table 1). Furthermore, as compared to the control, the biofilm treatment resulted in a considerable rise in soil chemical parameters including pH and organic carbon content. The pH of the soil rose from 5.4 to 6.3, becoming closer to ideal levels for the development of microorganisms and rice plants. A 15.2% rise in organic carbon content suggests that the overall quality of the soil has improved.

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Table 2. shows the variations in pH, soil organic carbon, and chlordane pesticide residual levels during a 90-day treatment period.

Parameter	Control	Biofilm	Biostimulation	Bioaugmentation
Chlordane content (mg/kg)	1.23 ± 0.05	0.39 ± 0.03*	0.85 ± 0.04	0.72 ± 0.05
Soil pH	5.4 ± 0.1	6.3 ± 0.1*	5.9 ± 0.1	6.0 ± 0.1
Organic carbon (%)	1.25 ± 0.04	1.44 ± 0.05*	1.35 ± 0.03	1.38 ± 0.04

*There is a significant difference ($p < 0.05$) between these values and the control.

3.3. Microbial Population and Soil Biological Activity

As a measure of soil microbial metabolism, the activity of dehydrogenase enzymes rose dramatically in the biofilm treatment, averaging 45.2 µg TPF/g soil/hour as opposed to the control's 20.3 µg TPF/g soil/hour ($p < .01$). Under comparison to the control, the overall microbial population doubled under the biofilm treatment (Figure 2).

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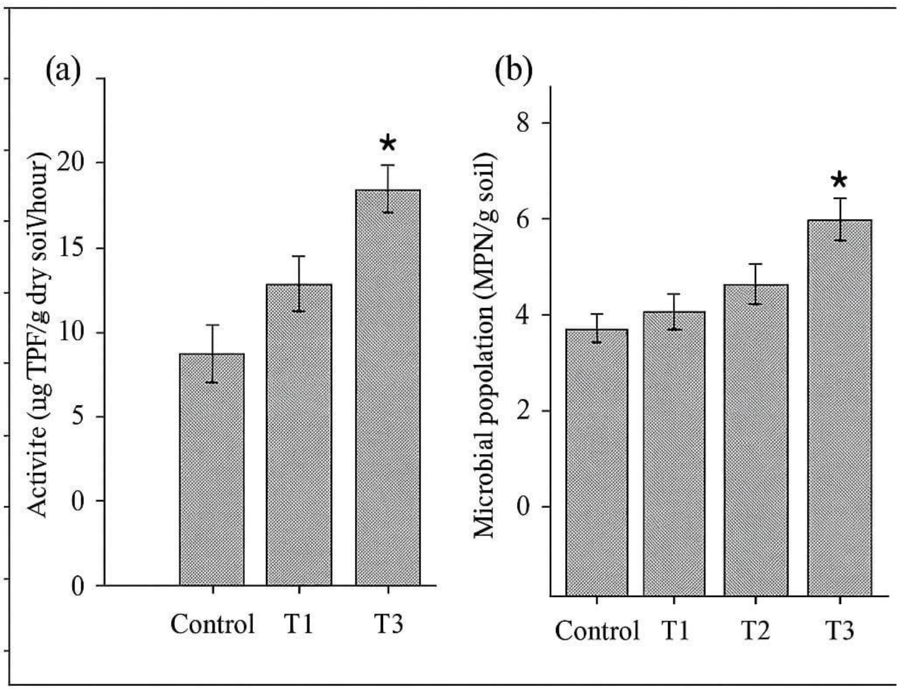

Figure 2. Shows The Soil Microbial Community and Dehydrogenase Enzyme Activity Following a 90-Day Treatment Period.

Activity of the enzyme dehydrogenase; (b) Microbial population (MPN/g soil). A significant difference from the control ($p < .01$) is indicated by an asterisk (*).

3.4. Effect on Rice Plant Yield and Growth

Agronomic indices of rice plants were significantly improved by biofilm treatment. The average height of the plants in the biofilm treatment was 95.4 cm, which was greater than the control's 82.7 cm ($p < .05$). In comparison to the control, the biofilm treatment resulted in a 28% increase in the quantity of productive tillers (Table 2).

Reviving rice fields with local bacterial biofilms was able to dramatically boost productivity, as seen by the dry milled grain yield in the biofilm treatment reaching 6.8 tons/ha, a considerable increase compared to the control of 5.1 tons/ha ($p < .05$).

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Table 3. Rice growth and yield metrics following biofilm treatment.

Parameter	Control	Biofilm	Biostimulation	Bioaugmentation
Plant height (cm)	**82.7 ± 2.1**	**95.4 ± 2.5***	**88.3 ± 2.0**	**90.1 ± 2.3**
Productive tillers	12.5 ± 0.7	16.0 ± 0.8*	14.1 ± 0.6	15.2 ± 0.7
Grain yield (ton/ha)	5.1 ± 0.3	6.8 ± 0.4*	5.9 ± 0.3	6.2 ± 0.3

*Values differ substantially from the control group ($p < 0.05$).

4. Discussion

4.1. Local Bacterial Biofilms' Efficiency in Bioremediation

According to the study's results, applying local bacterial biofilms a combination of Pseudomonas fluorescens, Acinetobacter sp., and Bacillus subtilis significantly decreased the residues of chlordane pesticides by as much as 68.4% over the course of 90 days (Table 1). These findings are consistent with research on the biodegradation of chlorpyrifos by Bacillus and Pseudomonas species, which, albeit using different kinds of pesticides, produced 33–52% breakdown in 14 days. The capacity of biofilms to generate exopolysaccharides (EPS), which boost the bioavailability of pesticide residues while shielding microorganisms from chemical stress, supports the primary mechanism of this breakdown.

4.2. Enhancement of Biological Activity and Soil Quality

An improvement in soil fertility was shown by the biofilm treatment's rise in soil pH (from 5.4 to 6.3) and organic carbon (15.2%) (Table 1). Dehydrogenase enzyme activity increased by 123% as a result of this occurrence (Figure 1), indicating that soil microbial function had recovered. This result is in line with the function of Plant Growth-Promoting Rhizobacteria (PGPR) in biofilms that produce EPS and IAA, promoting soil structure and nutrient cycling. Furthermore, the idea that biofilms establish microbial "hotspots" in the rhizosphere to sustain ecosystems is reinforced by the rise in soil microbial populations (Figure 2).

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4.3. Ecological Consequences and Agronomic Impact

In addition to pesticide breakdown, the biofilm treatment (Table 2) increased rice production by 33% (from 5.1 to 6.8 tons/ha) by stimulating plant development through the following mechanisms:

- Enhanced Nutrient Availability: Biofilm enhances phosphate solubilization and nitrogen fixation.
- Induction of Biotic Resistance: EPS's antimicrobial substances shield plants against infections.
- Enhancement of Root Structure: The biofilm matrix enhances soil aeration and water retention.

Nevertheless, its efficacy is contingent upon the bacterial strains' compatibility with regional agroecological circumstances. The advice for multi-location adaptation trials was based on studies of Bacillus siamensis and Lysinibacillus macroides, which revealed differences in plant growth responses based on soil type and climate.

4.4. Issues and Difficulties

Despite the promise, two contentious concerns should be noted:

- Possible Microbial Resistance: Prolonged pesticide exposure may lead to the selection of resistant strains, upsetting the equilibrium of the soil microbial population.
- Dependency on Environmental Conditions: Because enzymatic activity is inhibited in soils with low pH (<5.0) or excessive rainfall (>300 mm/month), biofilm efficacy declines.

4.5. Consequences for Agriculture Sustainability

The results back the shift to agriculture using less chemicals, which has consequences for:

- Economic: Applying biofilm can save the cost of pesticides and fertilizers by up to 40%.
- Environmental: Less chance of non-target toxicity and groundwater pollution.
- Social: Higher farmer income as a result of long-term increases in production.

4.6. Prospects for Further Research

In light of methodological constraints (Section 2.7), future studies ought to concentrate on:

- Creation of Multifunctional Consortia: Using nitrogen-fixing cyanobacteria and pesticide-degrading bacteria together to increase soil fertility without the need for outside assistance.
- Genetic alteration to increase biofilm resistance to harsh environments (high salinity, low pH) is known as adaptive biofilm engineering.
- Long-Term Impact Study: Tracking over five growing seasons to assess the stability and resistance risk of the soil microbial population.
- Integration with Digital Technologies: Using real-time soil and climatic data, machine learning is used to forecast biofilm performance.

5. Conclusions

By using three primary processes, this study demonstrates that the application of local bacterial biofilms (Bacillus subtilis, Pseudomonas fluorescens, and Acinetobacter sp.) greatly revitalizes pesticide-treated rice fields:

- Effective Bioremediation: Using microbial enzymatic activity in the exopolysaccharide matrix, chlordane pesticide residues can be reduced by up to 68.4% in 90 days.
- Soil Ecosystem Recovery: The restoration of soil biological processes is shown in increased soil pH (5.4 → 6.3), organic carbon (+15.2%), and dehydrogenase enzyme activity (+123%).
- Enhanced Productivity: Better root structure and nutrient availability resulted in a 33% increase in rice production (6.8 tons/ha).

By demonstrating the potential of biofilms as a multipurpose solution combining bioremediation, soil fertility enhancement, and sustained agricultural production, these findings contribute to scientific understanding. However, caution is needed when extrapolating the results because this technology's efficacy depends on:

- Agroecological Suitability: Reactions differ according on local pesticide usage trends, soil type, and climate.
- Technical Restrictions: LC-MS/MS, which is unavailable in situ, is necessary for the analysis of intermediate metabolites.

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- Temporal Scale: Only two growth seasons were used to track biofilm stability.

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